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Review

Developmental palaeontology in synapsids: the fossil record of ontogeny in mammals and their closest relatives

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The study of fossilized ontogenies in mammals is mostly restricted to postnatal and late stages of growth, but nevertheless can deliver great insights into life history and evolutionary mechanisms affecting all aspects of development. Fossils provide evidence of developmental plasticity determined by ecological factors, as when allometric relations are modified in species which invaded a new space with a very different selection regime. This is the case of dwarfing and gigantism evolution in islands. Skeletochronological studies are restricted to the examination of growth marks mostly in the cement and dentine of teeth and can provide absolute age estimates. These, together with dental replacement data considered in a phylogenetic context, provide life-history information such as maturation time and longevity. Palaeohistology and dental replacement data document the more or less gradual but also convergent evolution of mammalian growth features during early synapsid evolution. Adult phenotypes of extinct mammals can inform developmental processes by showing a combination of features or levels of integration unrecorded in living species. Some adult features such as vertebral number, easily recorded in fossils, provide indirect information about somitogenesis and hox-gene expression boundaries. Developmental palaeontology is relevant for the discourse of ecological developmental biology, an area of research where features of growth and variation are fundamental and accessible among fossil mammals.

Keywords: heterochrony; modularity; palaeohistology; growth; allometry; skeletochronology

1. INTRODUCTION

The study of major morphological transformations in mammals and their closest relatives has provided classic examples of the integration of embryological with palaeontological data. These include the discovery of the homologies of the mammalian ear ossicles and the later discovery of fossils that confirmed the hypothesized transformations (Macrini 2002). Other major examples are the origin of the alisphenoid bone in the lateral wall of the mammalian skull (Hopson & Rougier 1993), the secondary palate (Maier 1999) and that of the large mammalian brain and its relation to the new masticatory and middle ear anatomy (Rowe 1996). Another area concerns the direct inference from the fossil record of developmental processes, the 'rock record' of development, treated in this review. I examine the topic raised by Raff when he stated:

> Despite the impossibility of doing genetics on defunct animals and the difficulties in approaching development when only static objects are preserved, a great deal of information on reproduction and development can in some cases be reclaimed from fossils.
>
> (Raff 1996, p. 268)

The existing literature dealing with ontogeny in mammalian fossils is too broad and dispersed in time and places of publications as to be able to present a complete survey of it. A continuous attempt to make available the existing literature is presented in the website (www.developmental-palaeontology.net) accompanying this paper. Here, I review and summarize the major areas treated in those papers and discuss the great potential and scope of developmental palaeontology. Following convention, I refer to Synapsida as the amniote clade separating from Reptilia about 320 mybp (Kemp 2007) and leading to the modern crown-group of mammals, composed of monotremes, marsupials and placentals. Different clades of synapsids provide the best or sole examples for the major issues treated in this review, so by necessity no meaningful taxonomically ordered review is possible at present.

2. GROWTH ALLOMETRY IN FOSSILS

After Julian Huxley's (1932) classic 'Problems of relative growth', several authors used the newly introduced analytical tools to study fossil mammals, such as Hersch (1934) on an extinct clade of perissodactyls called brontotheres. A later revival in the study of growth heterochrony (Gould 1977) focused on patterns of relative growth in size and shape (Klingenberg 1998). In this approach, size is taken as a surrogate for time. This works better for mammals than for other groups of vertebrates, as they have determinate growth not so greatly influenced by external factors such as temperature.

Deviations from isometry in growth trajectories can lead to major changes in proportions and with that can

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generate novel morphologies (McNamara 1997), as in the skull evolution of fossil horses in which new growth patterns were associated with the evolution of new diets (Radinsky 1984). At a micro-level allometric growth can also generate morphological diversity, as among dog breeds based on the highly allometric growth of canids, in contrast to felids that exhibit cranial isometry and correspondingly less diversity (Sears *et al*. 2007).

McKinney & Schoch (1985) found that the evolution of horns in a phylogenetic series of brontotheres is not just an extension of a growth trajectory as had been first suggested by Hersch (1934). Instead, other changes were also involved, such as predisplacement (early onset of development) and acceleration in the rate of growth. Cranial ornaments in brontotheres have a positive allometry, as is the case in other groups of extinct vertebrates (Delfino & Sánchez-Villagra in press).

In ontogenetic scaling, the variation between two closely related species can be completely attributed to differences in size, as both species map onto a common ontogenetic trajectory. Differences result from the extension or truncation of growth (Weston 2003). Conversely, a change in developmental pattern can be inferred when the variation does not map on a single common trajectory.

There are methodological issues concerning the growth heterochrony approach. The relationship between chronological age and size is seldom exponential and more commonly sigmoidal (Godfrey & Sutherland 1995). This makes the usual logarithmic transformations typical of growth heterochrony studies not appropriate when allometric trajectories are not conserved, that is, in the case of 'shape dissociation' (Shea 1985). The use of chronological age in studies of heterochrony, instead of size as a proxy for age, is recommended but often impossible in the study of fossils. Methods to confront this problem are the use of skleletochronological techniques or the approach of sequence heterochrony. Geometric morphometric methods are also an alternative, and they dominate the current literature on shape analyses of both fossil and living taxa (Lawling & Polly 2010).

The approach of sequence heterochrony (Smith 2001) provides a methodology to study changes in the timing of events not characterized by size and shape parameters. By using the sequence of events as the criterion of standardization these methods avoid many of the problems that arise in the growth heterochrony approach. In essence, developmental events are incorporated into a matrix such that the timing of each event can be compared with every other event to form 'event pairs' as characters. Each pair of events may be assigned one of the three character states that represent the relative timing of these two events in a taxon. This kind of approach was recently applied to study hadrosaur dinosaur postcranials (Guenther 2009) and could be used to study discrete events in synapsid growth, such as the order of epiphysis closure in postcranial bones or ectocranial suture obliteration (Wilson & Sánchez-Villagra 2009).

Understanding the developmental processes underlying the patterns of allometry is a promising area of research. Mammalian examples include facial elongation in canids via mutations in the protein-coding region of *Runx2* (Sears *et al*. 2007) and the origin of the elongated digits of the bat wing via an accelerated rate of proliferation and differentiation of chondrocytes associated with higher levels of the bone morphogenetic protein, Bmp2 (Sears *et al*. 2006). The major role of fossils in this field will remain that of illuminating the background of actual, historical phenotypes, behind which the genetic and developmental mechanisms underlying those phenotypes can be addressed with molecular work on recent species (Wagner 2007).

3. ENVIRONMENTAL CHANGE, INSULARITY AND HETEROCHRONIC PROCESSES IN THE FOSSIL RECORD

Vrba (2004, 2005) argued that environmental changes occurring in geological time, such as climatic-driven changes occurring in the Neogene of North America, could have led to macroevolutionary events (origin of new taxa above the species level) through similar heterochronic changes occurring in several clades of mammals simultaneously. Climatic change can lead to evolutionary changes in size, as with the cooling and body size increase that occurred across clades about 3 Ma in Africa (Vrba 2004) or the decline in size of horses before their extinction in the Pleistocene of Alaska (Guthrie 2003). Such, in geological terms, simultaneous changes in size are associated with a 'heterochronic pulse', as also associated with the evolution of specialized saltatorial rodents from North America which evolved in desert areas of North America (Hafner & Hafner 1988; Vrba 2005).

The ecological context of development is relevant to understand cases of insular dwarfism and gigantism, for which the fossil record shows excellent examples. Following reproductive isolation on islands, there is a general tendency for small mammals to evolve towards larger size and larger species to evolve towards smaller size (Lomolino 2005). Drastic size changes are documented in the classic cases of fossil dwarf elephants, mammoths, hippopotami and deer (Sondaar 1977). For example, the extinct Sicilian elephant *Elephas falconeri*, is estimated to have reached a height of less than 1 m and a body mass of 100 kg, less than 1 per cent of the mass of their mainland ancestor (Roth 1992). On the other hand, a trend of increased body size ('gigantism') has been documented in numerous rodent taxa on islands (Millien & Damuth 2004).

The discovery of a new species of hominin from the Pleistocene of the Indonesian island of Flores, the celebrated *Homo floresiensis* (Brown *et al*. 2004) provides a prominent example of the necessity to consider ontogeny when studying fossils. *Homo floresienses* was only about 1 m in height and fully bipedal, with a reconstructed chimpanzee-like brain-size of 417 cm^3 in an approximately 30 kg body. This brain size seemed perplexing because this species made tools and lived recently, with a hominin ancestor possessing a comparatively much larger brain size (perhaps *H. erectus* with a brain volume of *ca* 900 cm^3). This is why some scholars argued that *H. floresiensis* is nothing more than a population of pygmies with a pathological condition including microcephaly (e.g. Jacob *et al*. 2006). Considering the allometric relations of brain to body size, the brain volume of *H. floresiensis* falls outside any expectations, irrespective of which hominid species among the potential candidates is hypothesized as ancestor (Lieberman 2009).

Weston & Lister (2009) provided quantitative evidence from a study of fossil hippos from Madagascar that extreme brain size reduction outside the range expected given allometric considerations are possible. Brain tissue is metabolically costly and thus it was hypothesized that this organ becomes smaller in lineages for which it is advantageous to save energy. The lack of simple ontogenetic scaling is not rare in cases of rapid evolutionary reduction in size. For example, Köhler & Moyá-Solá (2004) reported a significant reduction of the brain and sense organs in the fossil bovid *Myotragus* during its geographic isolation in the Mediterranean island of Majorca. In another example, Roth (1984) reported that insular dwarf species of fossil proboscidians are not simply paedomorphic in their postcranial proportions but show deviations most probably responding to locomotory and metabolic constraints and adaptations.

The allometric coefficients obtained from growth series in fossils can be used to define an allometric space. The examination of the relation in different clades between allometric space and diversification patterns in geological time is a rich potential avenue of research which has only started to be explored in other organisms, including ammonites (Gerber *et al*. 2008) and rodents (Wilson & Sánchez-Villagra 2010).

4. ONTOGENETIC VARIATION IN FOSSILS AND TAXONOMIC ISSUES

Owing to allometric relations during growth, individuals of the same species can have different shapes at different stages of development. The identification of ontogenetic series of fossils is not trivial and this can be accomplished most easily when large numbers of individuals in a stratigraphically controlled area are available—a very lucky and rare situation. This is regrettable, as it is desirable that the diagnosis of a taxon includes information concerning ontogenetic variation. More importantly, incorrect taxonomic assessments can be made because of preservational biases and lack of consideration of ontogenetic variation. There are many cases of taxa diagnosed on the basis of juveniles that later turn out to be junior synonyms of taxa previously described on the basis of adult specimens. For example, a detailed morphometric study of cynodont skulls showed that specimens previously referred to four species in two genera probably represent different ontogenetic stages of a single species (Abdala & Giannini 2000). A consideration of dental ontogenetic changes has led to taxonomic revisions of several taxa, including among many others rodents (Vucetich *et al*. 2005), ground sloths (Cartelle & De Iuliis 2006) and endemic ungulates from South America (Billet *et al*. 2008). Another example is provided by antlers, richly represented in the fossil record. Antlers can change dramatically in the course of life in species with a complex pattern, and their ontogenetic change has led to an overestimation in the number of species of fossil cervids (Lister 1990).

Consideration of postcranial structures in ontogeny and taxonomy in fossils is also relevant. Brinkman (1988) described the postcranial changes for two basal synapsid species of eupelycosaurians, *Ophiacodon* and *Dimetrodon*, and found major similarities in the sequence of ossification events between these and the more basal tetrapod *Eryops* (Bakker's 1982). Most importantly, he concluded that size is a poor indication of the stage of development. As the anatomical information supported allocation of specimens of different sizes to the same species, this observation implies that these basal synapsids did not have a mammalian kind of growth and thus for them size is not a good proxy for age.

5. MODULARITY

One way in which mammalian fossils contribute to the understanding of developmental aspects is through the preservation of combinations of features which we do not see in living taxa. This is related to modularity, which is fundamentally a developmental concept. Modularity can be defined as the division of larger structures or processes into autonomous and internally integrated parts (Klingenberg 2008).

Olson & Miller (1958) presented the first quantitative examination of modularity. They argued that during evolution trait changes do not occur independently, but may be correlated because of proximity in development or function. They proposed the study of correlation among traits as a methodology to examine morphological integration. Clusters, highly correlated trait groups, could be derived quantitatively. Olson & Miller (1958) treated fossils very prominently, for example referring to the apparently non-modular evolution of dental cusps in a lineage of the condylarth *Hyopsodus*.

Fossils can expand the morphological space occupied by a clade, by showing relationships among traits not present in living forms. For example, the derived cranial morphology of the (extinct) sabre-toothed cat *Smilodon fatalis* shows a pattern of cranial integration different from that of any of the other 105 species (97 extant and eight fossil) that Goswami (2006) examined in her comprehensive study of mammalian cranial modularity (see also Porto *et al*. 2008). In *Smilodon*, the facial skeleton and the enlarged canines form two separate modules instead of the single anterior oral–nasal group characteristic of all mammals, including monotremes. Other non-felid sabre-toothed carnivorans examined by Goswami (2006) were two nimravid species, which conformed to the standard pattern. I suggest that the different timing of tooth replacement between *Smilodon* and nimravids is causally correlated with their different modularity pattern. Whereas, in *Smilodon* a deciduous sabre erupts at a young age, enabling the animal to hunt at a young age; in nimravids there is a late appearance of the deciduous sabre (Bryant 1988), resulting in the later preservation of the ancestral pattern of skull integration.

6. TOOTH DEVELOPMENT AND SKELETOCHRONOLOGY

In the first half of the twentieth century embryological and palaeontological studies of mammalian teeth were not connected at all. The first concerned studies of dental lamina up to the deposition of enamel and dentine. Palaeontologists only studied the morphology of fully erupted teeth. Later work on molar cusp development (Marshall & Butler 1966) brought a developmental perspective to the study of dental variation which influenced later work on fossils (Clemens & Lillegraven

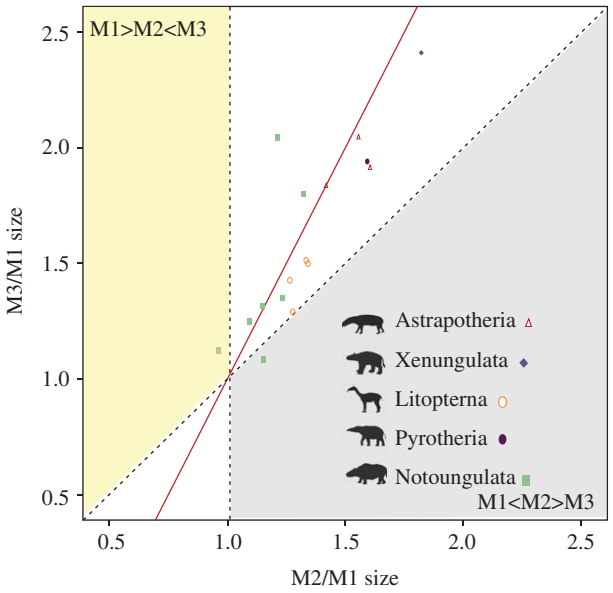

Figure 1. Empirical test with extinct placentals of the cascade model of tooth development of Kavanagh *et al.* (2007). The line is the relationship predicted by the model, which can account for the white region. Molar proportions in morphospace are plotted for the following five major fossil clades (1) Notoungulata: *Altitypotherium paucidens* and *Trachytherus spegazzinianus* (Mesotheridae), **Hegetotherium mirabile* and *Hemihegetotherium trilobus* (Hegetotheridae), **Archaeotypotherium pattersoni* (Typotheria); *Nesodon imbricatus* and *Adinotherium ovinum* (Toxodontidae); (2) Litopterna: *Prothoatherium colombianus, Protolipterna ellipsodontoides, Adianthus godoyi* and *Macrauchenia patachonica*; (3) Astrapotheria: *Xenastrapotherium christi*, *Astrapotherium magnum* and *Trigonostylops apthomasi*; (4) Pyrotheria: *Pyrotherium romeri*; (5) Xenungulata: *Carodnia vieirai*. The names of the two species of notoungulates that do not fit the model are marked (*) above. Please refer to the electronic supplementary material for sources of data and other details.

1986). Most recent work concerns the correlation of traits during development which are usually atomized during phylogenetic analyses of living and fossil species (Kangas *et al.* 2004) and the generation of size gradients in the molar row as determined by a balance of inhibitor and activator molecules, the 'cascade' model of Kavanagh *et al.* (2007). The latter is impressive because of its simplicity and great power in predicting the empirical data for living mammals (Polly 2007). Raff (2007, p. 916) suggested that fossils could test Kavanagh *et al.*'s developmental model of phenotype generation. I follow here this suggestion and test its applicability to five extinct and enigmatic clades of mammals from South America, which so far, have been studied primarily in the context of biostratigraphy and palaeoecology (e.g. Croft 2007). As can be seen in figure 1, some fossil species fall outside the confidence interval predicted by the developmental model. These species evolved mechanisms that surmounted the constraint implied by the otherwise uniform pattern of molar gradients in living species, which can be hypothesized to have been present in the last common ancestor of therian mammals (Polly 2007). New ecological factors must have been involved, as the notoungulate fossils, which constitute the exception, evolved herbivorous diets and inhabited open environments which produced a particularly abrasive regime for the dentition. This kind of ecology is not unique, so other factors must have played a role. For example, the pattern of dental replacement could have produced developmental constraints to masticatory architecture, as has been hypothesized for marsupial mammals (Werdelin 1987). To summarize: simple molar proportions in fossil taxa of otherwise only taxonomic use can become a rich source of information on developmental evolution when examined in a new conceptual framework and can stimulate integrative studies of ecology and development (Renvoisé *et al.* 2009).

The occlusal morphology of teeth can change radically during life time, with the wearing of cusps until their disappearance and the exposure of dental tissues originally covered by enamel in younger individuals (King *et al.* 2005). Degree of wear can be used for relative age determination in fossils, but this approach has many disadvantages, including the variation in rates and patterns of tooth wear even within populations as well as regional variation, and the subjectivity involved in measuring wear without the use of sophisticated quantitative techniques (Kaiser & Brinkmann 2006). In the late 1960s, the use of layers in tooth cement and dentine to estimate age started to receive much attention (Stallibrass 1982). These layers are deposited in regular, seasonal cycles, as in the case of tree rings, and can be thus counted to give absolute ages of individuals (Laws 1952). Layers in the dentine and cement are visible with standard microscopy after using simple histological techniques. Differences in metabolic rate determined in part by environmental seasonality cause the periodicity of layer deposition. Cement and dentine are hard tissues and are seldom subject to remodelling or resorption. This is not the case for periosteal bone, in which annually deposited layers also occur, but which are subject to much change and obliteration during growth (Hall 2005).

As mastodon and mammoth tusks are built of laminated structures that grew incrementally on a temporal basis, their analyses can provide information on age, growth rates and age at sexual maturity of individual animals, as well as detailed mortality profiles for populations (Fisher 2001). The palaeoenvironmental context of these integrative life history and demographic studies can be attained with stable isotope analyses of tusks, which provide information on temperature and diet at different times of the animal's life (Fox & Fisher 2001).

Scholars have tried to establish the degree to which reproductive parameters such as gestation length can be inferred based on dental growth data. For example, the age at first molar eruption has been correlated with the timing of weaning and overall longevity (Smith 1986). Based on the work of the late Adolph Schultz, a relationship between the relative order of eruption of molars and second-generation antemolar teeth (premolars, canines, incisors), and growth and maturation has been proposed (Smith 2000). According to 'Schultz's rule', early eruption of molars and late eruption of antemolars is correlated with rapid growth, early sexual maturation and short lifespan. On the other hand, late eruption of the molars and early eruption of the secondary dentition is correlated with 'slow' life-history traits. These features have been mostly studied in primates, particularly regarding reconstruction of life-history variables in early hominids (Dean 2006). Hominoids have lower mortality

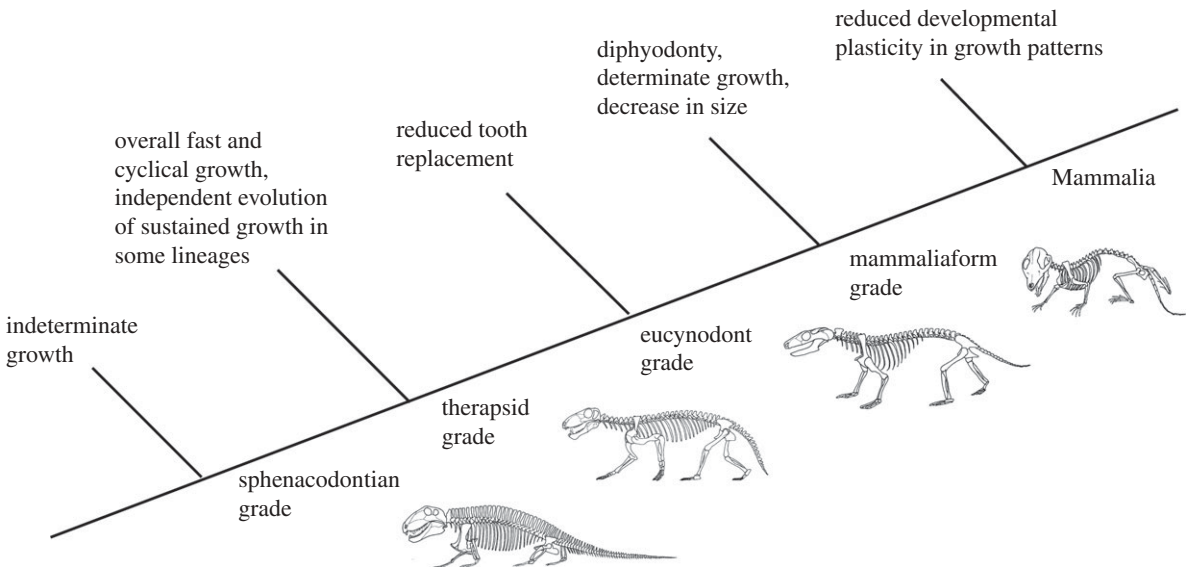

Figure 2. Major changes in growth and dental replacement patterns during synapsid evolution. Animal sketches modified from Kemp (2007) and references therein.

rates than do other catarrhines, the Old World monkeys. Whereas early reproduction tends to be favoured in Old World monkeys, delayed reproduction into more mature ages characterizes hominoids (Kelley 2002).

The extent to which non-primates follow this 'rule' is not clear (Asher & Olbricht 2009); and even within primates, exceptions to Schultz's rule have been found, as in the early eruption of the tooth comb in lemurs irrespective of the kind of life history (Godfrey *et al*. 2005). As in so many other aspects of morphological evolution, the pervasive influence of phylogeny is also reflected in dental and growth patterns, for example in the extinct lemurs of Madagascar. These were diverse and many were very large and reminiscent superficially of anthropoids (Schwartz *et al*. 2002). The extinct, chimpanzee-sized lemur *Palaeopropithecus* exhibits a pattern of dental development similar to that of its closest living phylogenetic relative, the indri (*Indri indri*), as opposed to a pattern concordant with anthropoids as one would expect based on the large anthropoid-like size of this species. Another unrelated example concerns the also extinct Holocene form, *Megaladapis edwardsi*. This species was shown to exhibit a basicranium with features superficially anthropoid-like, but which upon closer examination based on fossils of juveniles of this species clearly turn out to be typical of lemurs (MacPhee 1987).

7. DEVELOPMENTAL PALAEONTOLOGY IN NON-MAMMALIAN SYNAPSIDS AND THE ORIGIN OF LIVING MAMMALS

The evolution of lactation in mammals is correlated with dental features such as the late eruption of the first functional teeth. Mammals are diphyodont, as they produce only two tooth generations and replacement is retarded, with a juvenile and an adult dentition. This is associated with determinate growth, i.e. rapid juvenile growth ending in a set adult size (Kielan-Jaworowska *et al*. 2004). Thanks to a combination of dental eruption pattern data with the growing palaeohistological record of pre-mammalian synapsid evolution (Ray *et al*. 2009) it is possible to trace the origin of these features (figure 2). In palaeohistological studies, the detection of fibrolamellar bone is a major issue, as this indicates rapid osteogenesis and with that overall fast growth (de Ricqlès 1972), also related with endothermy. This kind of bone is widespread among therapsids (Chinsamy & Hurum 2006).

The earliest synapsids, including sphenacodontians, preserved the characteristic indeterminate growth of basal amniotes. In therapsids growth rate increased as indicated by fibrolamellar bone-histology. Maier (1999) hypothesized that closure of the maxillary secondary palate evolved independently in some therapsid-grade forms, including cynodonts, and in mammals, and might have increased the mechanical strength of the skull being an important change allowing neonates to suckle. This feature could have led to a higher metabolic rate, also related to the growth pattern. At the eucynodont node, tooth replacement was reduced towards the mammalian pattern.

Population studies of fossils (with good stratigraphic control) can provide information on growth. If all adults are of the same size, that would speak for determinate growth. This is what has been reported for a population study of *Morganucodon* (Parrington 1971), a late Triassic–early Jurassic diphyodont form closely related to the crown group Mammalia (Kielan-Jaworowska *et al*. 2004). Establishment of diphyodonty at this mammaliaform node or perhaps already in the more basal trithelodont node (Kemp 2005) was most probably correlated with the establishment of lactation, although these features were absent in *Sinocodon*, the sister group of mammaliaformes (Luo *et al*. 2004).

Early mammals are characterized by reduced developmental plasticity (Chinsamy & Hurum 2006), with more stable growth patterns than the often recorded bouts of rapid and slow growth typical of earlier synapsids. The capacity to stop or reduce growth during adverse environmental conditions must have characterized premammalian synapsids, as documented by the palaeohistological record (Ray *et al*. 2009). An increasing homeostatic ability characterizes synapsid evolution

towards mammalian origins: through a high metabolic rate, a constant internal environment was maintained (Kemp 2007).

Within mammals, changes in developmental patterns are also recorded by the fossil record. A marsupial-like pattern of tooth replacement in Cretaceous and Paleocene stem-metatherians was documented using X-ray-computed tomography (Cifelli & Muizon 1998). Metatherians are derived in that only the last premolar is replaced postnatally in each jaw (Rougier *et al.* 1998). As this mode of dental replacement has been correlated with the marsupial mode of reproduction involving a short gestation length and a very altricial condition of birth, these life-history traits were hypothesized to have been present already in the Cretaceous (but see van Nievelt & Smith 2005).

8. RARE EXCEPTIONAL PRESERVATION OF ONTOGENETIC STAGES IN MAMMALS

Contrary to the celebrated cases of dinosaur and other reptilian embryos in the fossil record (Delfino & Sánchez-Villagra in press), mammalian embryos in the fossil record are almost non-existent or mainly constitute just a curiosity because of poor preservation, as exemplified by horse and bat embryos from the Eocene of Messel in Germany (Gruber & Micklich 2007). A recent discovery may provide an exception to this.

A newly described 47.5 Myr-old stem whale from Pakistan, *Maiacetus inuus*, was found with a smaller individual inside its body cavity. Gingerich *et al.* (2009) interpreted the smaller specimen as lying in its *in vivo* position within the uterus of an adult. The fossil was therefore interpreted as a pregnant female about to give birth. The head-first delivery position of the alleged foetus is like that of land mammals, indicating a terrestrial mode of life unlike modern whales. The head-forward position of live-bearing (viviparous) ichthyosaurs is well documented (Maxwell & Caldwell 2003). The well-developed set of teeth in the foetus was interpreted as a sign of precociality, suggesting that *Maiacetus* newborns were probably active immediately after birth. Like other stem-cetaceans, *Maiacetus* had four legs modified for foot-powered swimming but could probably support its weight on land with their flipper-like limbs.

Thewissen & McLellan (2009) argued against the interpretation made by Gingerich *et al.* (2009): the position of the smaller individual relative to the vertebral series of the older individual is too cranial and the absence of its caudal vertebrae are more consistent with an interpretation of the smaller individual as a prey item. Thewissen & McLellan (2009) stressed the importance of taphonomic studies in order to be able to interpret fossils confidently (Raff *et al.* 2006).

9. DEVELOPMENTAL INFERENCES DRAWN FROM STUDIES OF ADULT PHENOTYPES

There are indirect ways to study ontogeny in fossils, including the growth record studied via palaeohistology. Fossils of adult individuals can also be informative by virtue of preserving phenotypes with an immediate, clear correlation to a specific developmental process. An example is the relation between adult vertebral numbers and the early embryological determination of the number of segments and boundary regions. There is a correspondence of vertebral numbers with somitogenesis and hox-gene boundaries (Burke *et al.* 1995). Based on this premise, Müller *et al.* (in press) examined the rich amniote fossil record and reconstructed the patterns of somitogenesis and the evolution of presacral region boundaries. They traced back the developmental canalization or conservatism in mammalian presacral numbers to the origin of synapsids. Establishment of the almost constant number of seven cervical vertebrae occurred at the mammaliaform node. I hypothesize that the increase in metabolic rate at this point of synapsid evolution (Kemp 2007) is causally correlated with this change. Based on the high frequency of mortality of human foetuses and juveniles with abnormal vertebral numbers, pleiotropic effects relating to mutations in *Hox* regulation affecting not only axial skeleton but also cell proliferation were proposed (Galis *et al.* 2006). Only mammals with a low metabolic rate show deviations from the standard cervical number, and this feature is also related to a lower incidence of cancer.

Asher & Lehmann (2008) reported on the coincidence of the supernumerary presacral numbers of afrotherian mammals with late dental eruption in that clade, and the presence of a similar phenotypic suite in humans with the genetic pathology cleidocranial dysplasia. Both vertebral count and dental eruption can be studied in fossils, and the examination of well-preserved stem members of the relevant groups could potentially reveal fundamental changes in developmental patterns in placental evolution.

10. CONCLUSIONS

An allometric or 'growth heterochrony' approach (Smith 2001) has dominated the literature on development in fossils. Richtsmeier (2003, p. 162) defined growth as 'change in the arrangement of component parts with increase in spatial dimensions occurring over time'; this is usually seen in contrast to 'development', which includes pattern formation and cell differentiation. Growth is thus considered just an aspect of development. These boundaries also follow the classic discussion of Needham (1933), in which differentiation, or the increase in complexity and organization, is distinguished from the increase in dimensions characteristic of growth. In the case of mammals, the study of fossilized ontogenies is mostly restricted to postnatal and almost exclusively late stages of growth; but it can nevertheless deliver great insights into life history in extinct forms and evolutionary mechanisms affecting all aspects of development.

The attention that developmental biologists have given to palaeontological studies have concentrated on direct (Gostling *et al.* 2007) or indirect (Raff 2007) considerations of development via inferences about the mode and timing of major macroevolutionary events. This is particularly relevant when studying stem-groups, the extinct species which show the time and mode in which the acquisition of diagnostic features of living taxa arose (Donoghue 2005), as in the example above on the origin of mammals within synapsids.

Palaeontological studies of development can be integrated and be relevant for the discourse of ecological

developmental biology (Gilbert & Epel 2008), an area of research where late growth and variation are fundamental and accessible as units of study among fossil mammals. The numerous dental adaptations and variations preserved in fossils, with their direct correlation to diet and ecology, are a fertile subject of study, as in the example above of extinct South American ungulates. There is no doubt that the conceptual tools of developmental biology can provide new and productive ways to understand evolution in deep time.

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REFERENCES

Abdala, F. & Giannini, N. P. 2000 Gomphodont cynodonts of the Chañares Formation: The analysis of an ontogenetic sequence. *J. Vert. Paleontol.* **20**, 501–506. (doi:10.1671/0272-4634(2000)020[0501:GCOTCA]2.0.CO;2)

Asher, R. J. & Lehmann, T. 2008 Dental eruption in afrotherian mammals. *BMC Biol.* **6**, 14. (doi:10.1186/1741-7007-6-14)

Asher, R. J. & Olbricht, G. 2009 Dental ontogeny in *Macroscelides proboscideus* (Afrotheria) and *Erinaceus europaeus* (Lipotyphla). *J. Mamm. Evol.* **16**, 99–115. (doi:10.1007/s10914-009-9105-2)

Bakker, R. T. 1982 Juvenile–adult habitat shift in Permian fossil reptiles and amphibians. *Science* **217**, 53–55. (doi:10.1126/science.217.4554.53)

Billet, G., de Muizon, C. & Mamani Quispe, B. 2008 Late Oligocene mesotheriids (Mammalia, Notoungulata) from Salla and Lacayani (Bolivia). *Zool. J. Linn. Soc.* **152**, 153–200.

Brinkman, D. 1988 Size-independent criteria for estimating relative age in *Ophiacodon* and *Dimetrodon* (Reptilia, Pelycosauria) from the Admiral and lower Belle Plains formations of west-central Texas. *J. Vert. Paleontol.* **8**, 172–180.

Brown, P. *et al.* 2004 A new small-bodied hominin from the late Pleistocene of Flores, Indonesia. *Nature* **431**, 1055–1061. (doi:10.1038/nature02999)

Bryant, H. N. 1988 Delayed eruption of the deciduous upper canine in the sabretoothed carnivore *Barbourofelis lovei* (Carnivora, Nimravidae). *J. Vert. Paleontol.* **8**, 295–306.

Burke, A. C., Nelson, C. E., Morgan, B. A. & Tabin, C. 1995 Hox genes and the evolution of vertebrate axial morphology. *Development* **212**, 333–346.

Cartelle, C. & De Iuliis, G. 2006 *Eremotherium laurillardi* (Lund) (Xenarthra, Megatheriidae), the Panamerican giant ground sloth: taxonomic aspects of the ontogeny of skull and dentition. *J. Syst. Palaeontol.* **4**, 199–209. (doi:10.1017/S1477201905001781)

Chinsamy, A. & Hurum, J. H. 2006 Bone microstructure and growth patterns of early mammals. *Acta Palaeontol. Pol.* **51**, 325–338.

Cifelli, R. L. & de Muizon, C. 1998 Tooth eruption and replacement pattern in early marsupials. *Compt. Rend.l'Acad. Sci. Sér. II, Sci.Terr. Planèt.* **326**, 215–220.

Clemens, W. A. & Lillegraven, J. A. 1986 New Late Cretaceous, North American advanced therian mammals that fit neither the marsupial nor eutherian molds. *Contrib. Geol. Univ. Wyom. Spec. Pap.* **3**, 55–85.

Croft, D. A. 2007 The middle Miocene (Laventan) Quebrada Honda fauna, southern Bolivia, and a description of its notoungulates. *Palaeontology* **50**, 277–303. (doi:10.1111/j.1475-4983.2006.00610.x)

Dean, M. C. 2006 Tooth microstructure tracks the pace of human life-history evolution. *Proc. R. Soc. B* **273**, 2799–2808. (doi:10.1098/rspb.2006.3585)

Delfino, M. & Sánchez-Villagra, M. R. In press. A survey of the rock record of reptilian ontogeny. *Sem. Cell Dev. Biol.* (doi:10.1016/j.semcdb.2009.11.007)

de Ricqlès, A. 1972 Recherches paléohistologiques sur les os longs des Tétrapodes. III, Titanosuchiens Dinocéphales et Dicynodontes. *Ann. Paléontol. (Vertébrés)* **58**, 17–60.

Donoghue, P. C. J. 2005 Saving the stem-group: a contradiction in terms. *Paleobiology* **31**, 553–558.

Fisher, D. C. 2001 Season of death, growth rates, and life history of North American mammoths. In *Proc. Int. Conf. Mammoth Site Studies* (ed. D. West). University of Kansas Publications in Anthropology, 22, pp. 121–135.

Fox, D. L. & Fisher, D. C. 2001 Stable isotope ecology of a late Miocene population of *Gomphotherium* (Mammalia, Proboscidea) from Port of Entry Pit, Oklahoma: diet, climate and diagenesis. *PALAIOS* **16**, 279–293.

Galis, F., van Dooren, T. J. M., Feuth, H., Ruinard, S., Witkam, A., Steigenga, M. J., Metz, J. A. J. & Wijnaendts, L. C. D. 2006 Extreme selection against homeotic transformations of cervical vertebrae in humans. *Evolution* **60**, 2643–2654.

Gerber, S., Eble, G. J. & Neige, P. 2008 Allometric space and allometric disparity: a developmental perspective in the macroevolutionary analysis of morphological disparity. *Evolution* **62**, 1450–1457. (doi:10.1111/j.1558-5646.2008.00370.x)

Gilbert, S. F. & Epel, D. 2008 *Ecological developmental biology.* Sunderland, MA: Sinauer Associates.

Gingerich, P. D. *et al.* 2009 New protocetid whale from the middle Eocene of Pakistan. *PLoS ONE* **4**, e4366. (doi:10.1371/journal.pone.0004366)

Godfrey, L. R. & Sutherland, M. R. 1995 Flawed inference: why size-based tests of heterochronic processes do not work. *J. Theor. Biol.* **172**, 43–61. (doi:10.1006/jtbi.1995.0004)

Godfrey, L. R., Samonds, K. E., Wright, P. C. & King, S. J. 2005 Schultz's unruly rule: dental developmental sequences and schedules in smallbodied, folivorous lemurs. *Folia Primatol.* **76**, 77–99. (doi:10.1159/000083615)

Gostling, N. J., Donoghue, P. C. J. & Bengtson, S. 2007 The earliest fossil embryos begin to mature. *Evol. Dev.* **9**, 206–207.

Goswami, A. 2006 Cranial modularity shifts during mammalian evolution. *Am. Nat.* **168**, 270–280. (doi:10.1086/505758)

Gould, S. J. 1977 *Ontogeny and phylogeny.* Cambridge, MA: Belknap Press.

Gruber, G. & Micklich, N. 2007 *Messel—treasures of the Eocene*. Darmstadt, Germany: Hessisches Landesmuseum.

Guenther, M. F. 2009 Influence of sequence heterochrony on hadrosaurid dinosaur postcranial development. *Anat. Rec.* **292**, 1427–1441. (doi:10.1002/ar.20988)

Guthrie, R. D. 2003 Rapid body size decline in Alaskan Pleistocene horses before extinction. *Nature* **426**, 169–171. (doi:10.1038/nature02098)

Hafner, J. C. & Hafner, M. S. 1988 Heterochrony in rodents. In *Heterochrony in evolution: a multidisciplinary approach* (ed. M. L. McKinney), pp. 217–235. New York, NY: Plenum Press.

Hall, B. K. 2005 *Bones and cartilage*. Amsterdam, The Netherlands: Elsevier Academic.

Hersch, A. H. 1934 Evolutionary relative growth in titanotheres. *Am. Nat.* **68**, 537–561.

Hopson, J. A. & Rougier, G. W. 1993 Braincase structure in the oldest known skull of a therian mammal: implications for mammalian systematics and cranial evolution. *Am. J. Sci.* **293A**, 268–299.

Jacob, T. *et al.* 2006 Pygmoid Australomelanesian *Homo sapiens* skeletal remains from Liang Bua, Flores. *Proc. Natl Acad. Sci. USA* **103**, 13421–13426. (doi:10.1073/pnas.0605563103)

Kaiser, T. M. & Brinkmann, G. 2006 Measuring dental wear equilibriums. *Palaeogeogr., Palaeoclim., Palaeoecol.* **239**, 221–240. (doi:10.1016/j.palaeo.2006.01.013)

Kangas, A. T., Evans, A. R., Thesleff, I. & Jernvall, J. 2004 Nonindependence of mammalian dental characters. *Nature* **432**, 211–214. (doi:10.1038/nature02927)

Kavanagh, K. D., Evans, A. R. & Jernvall, J. 2007 Predicting evolutionary patterns of mammalian teeth from development. *Nature* **449**, 427–433. (doi:10.1038/nature06153)

Kelley, J. 2002 Life history evolution in Miocene and extant apes. In *Human evolution through developmental change* (eds N. Minugh-Purvis & K. J. McNamara), pp. 223–248. Baltimore, MD: Johns Hopkins University Press.

Kemp, T. S. 2005 *The origin and evolution of mammals*. Oxford, UK: Oxford University Press.

Kemp, T. S. 2007 The origin of higher taxa: macroevolutionary processes, and the case of the mammals. *Acta Zool.* (*Stockholm*) **88**, 3–22. (doi:10.1111/j.1463-6395.2007.00248.x)

Kielan-Jaworowska, Z., Cifelli, R. L. & Luo, X. 2004 *Mammals from the age of dinosaurs. Origins, evolution and structure*. New York, NY: Columbia University Press.

King, S. J., Arrigo-Nelson, S. J., Pochron, S. T., Semprebon, G. M., Godfrey, L. R., Wright, P. C. & Jernvall, J. 2005 Dental senescence in a long-lived primate links infant survival to rainfall. *Proc. Natl Acad. Sci. USA* **102**, 16 579–16 583. (doi:10.1073/pnas.0508377102)

Klingenberg, C. P. 1998 Heterochrony and allometry: the analysis of evolutionary change in ontogeny. *Biol. Rev.* **73**, 79–123. (doi:10.1017/S000632319800512X)

Klingenberg, C. P. 2008 Morphological integration and developmental modularity. *Ann. Rev. Ecol. Syst.* **39**, 115–132.

Köhler, M. & Moyà-Solà, S. 2004 Reduction of brain and sense organs in the fossil insular bovid *Myotragus*. *Brain Behav. Evol.* **63**, 125–140.

Lawling, A. M. & Polly, P. D. 2010 Geometric morphometrics: recent applications to the study of evolution and development. *J. Zool.* **280**, 1–7. (doi:10.1111/j.1469-7998.2009.00620.x)

Laws, R. M. 1952 A new method of age determination for mammals. *Nature* **169**, 972–973. (doi:10.1038/169972b0)

Lieberman, D. E. 2009 Palaeoanthropology: *Homo floresiensis* from head to toe. *Nature* **459**, 41–42. (doi:10.1038/459041a)

Lister, A. M. 1990 Critical reappraisal of the middle Pleistocene deer species '*Cervus*' *elaphoides* Kahlke. *Quaternaire* **3–4**, 175–192.

Lomolino, M. V. 2005 Body size evolution in insular vertebrates: generality of the island rule. *J. Biogeogr.* **32**, 1683–1699. (doi:10.1111/j.1365-2699.2005.01314.x)

Luo, Z.-X., Kielan-Jaworowska, Z. & Cifelli, R. L. 2004 Evolution of dental replacement in mammals. *Bull. Carnegie Mus. Nat. Hist.* **36**, 159–175. (doi:10.2992/0145-9058(2004)36[159:EODRIM]2.0.CO;2)

MacPhee, R. D. E. 1987 Basicranial morphology and ontogeny of the extinct giant lemur *Megaladapis*. *Am. J. Phys. Anthropol.* **74**, 333–355. (doi:10.1002/ajpa.1330740307)

Macrini, T. 2002 Quantitative comparison of ontogenetic and phylogenetic character changes in the synapsid mandible and auditory region. *J. Mammal Evol.* **9**, 185–208. (doi:10.1023/A:1022667116022)

Maier, W. 1999 On the evolutionary biology of early mammals: with methodological remarks on the interaction between ontogenetic adaptation and phylogenetic transformation. *Zool. Anzeiger.* **238**, 55–74.

Marshall, P. M. & Butler, P. M. 1966 Molar cusp development in the bat, *Hipposideros beatus*, with reference to the ontogenetic basis of occlusion. *Arch. Oral Biol.* **11**, 949–965. (doi:10.1016/0003-9969(66)90197-X)

Maxwell, E. E. & Caldwell, M. W. 2003 First record of live birth in Cretaceous ichthyosaurs: closing an 80 million year gap. *Proc. R. Soc. Lond. B* **270**(Suppl. 1), S104–S107. (doi:10.1098/rsbl.2003.0029)

McKinney, M. L. & Schoch, R. 1985 Titanothere allometry, heterochrony, and biomechanics: revising an evolutionary classic. *Evolution* **39**, 1352–1363. (doi:10.2307/2408791)

McNamara, K. J. 1997 *Shapes of time*. Baltimore, MD: John Hopkins University Press.

Millien, V. & Damuth, J. 2004 Climate change and size evolution in an island rodent species: new perspectives on the island rule. *Evolution* **58**, 1353–1360.

Müller, J., Scheyer, T. M., Head, J. J., Barrett, P., Werneburg, I., Ericson, P. G. P., Pol, D. & Sánchez-Villagra, M. R. In press. Homeotic effects, somitogenesis and the evolution of vertebral numbers in recent and fossil amniotes. *Proc. Natl Acad. Sci. USA*.

Needham, J. 1933 On the dissociability of the fundamental processes in ontogenesis. *Biol. Rev.* **8**, 180–223. (doi:10.1111/j.1469-185X.1933.tb01153.x)

Olson, E. C. & Miller, R. L. 1958 *Morphological integration*. Chicago, IL: University of Chicago Press.

Parrington, F. R. 1971 On the Upper Triassic mammals. *Phil. Trans. R. Soc. Lond. B* **261**, 231–272. (doi:10.1098/rstb.1971.0055)

Polly, P. D. 2007 Development with a bite. *Nature* **449**, 413–415. (doi:10.1038/449413a)

Porto, A., de Oliveira, F. B., Shirai, L. T., De Conto, V. & Marroig, G. 2008 The evolution of modularity in the mammalian skull I: morphological integration patterns and magnitudes. *Evol. Biol.* **36**, 118–135. (doi:10.1007/s11692-008-9038-3)

Radinsky, L. 1984 Ontogeny and phylogeny in horse skull evolution. *Evolution* **38**, 1–15. (doi:10.2307/2408541)

Raff, R. A. 1996 *The shape of life*. Chicago, IL: University of Chicago Press.

Raff, R. A. 2007 Written in stone: fossils, genes and evo-devo. *Nat. Genet.* **8**, 911–920.

Raff, E. C., Villinski, J. A., Turner, F. R., Donahue, P. C. & Raff, R. A. 2006 Experimental taphonomy: feasibility of fossil embryos. *Proc. Natl Acad. Sci. USA* **103**, 5846–5851. (doi:10.1073/pnas.0601536103)

Ray, S., Bandyopadhyay, S. & Deblina Bhawal, D. 2009 Growth patterns as deduced from bone microstructure of some selected neotherapsids with special emphasis on dicynodonts: phylogenetic implications. *Palaeoworld* **18**, 53–66. (doi:10.1016/j.palwor.2008.09.001)

Renvoisé, E., Evans, A. R., Jebrane, A., Labruère, C., Laffont, R. & Montuire, S. 2009 Evolution of mammal tooth patterns: new insights from a developmental prediction model. *Evolution* **63**, 1327–1340. (doi:10.1111/j.1558-5646.2009.00639.x)

Richtsmeier, J. T. 2003 Growth. In *Keywords and concepts in evolutionary developmental biology* (eds B. K. Hall & W. M. Olson), pp. 161–169. Cambridge, MA: Harvard University Press.

Roth, V. L. 1984 How elephants grow: heterochrony and the calibration of developmental stages in some living and fossil species. *J. Vert. Paleo.* **4**, 126–145.

Roth, V. L. 1992 Inferences from allometry and fossils: dwarfing of elephants on islands. *Oxf. Surv. Evol. Biol.* **8**, 259–288.

Rowe, T. 1996 Coevolution of the mammalian middle ear and neocortex. *Science* **273**, 651–654. (doi:10.1126/science.273.5275.651)

Schwartz, G. T., Samonds, K. E., Godfrey, L. R., Jungers, W. L. & Simons, E. L. 2002 Dental microstructure and life history in subfossil Malagasy lemurs. *Proc. Natl Acad. Sci. USA* **99**, 6124–6129. (doi:10.1073/pnas.092685099)

Sears, K. E., Behringer, R. R., Rasweiler, J. J. & Niswander, L. A. 2006 Development of bat flight: morphologic and molecular evolution of bat wing digits. *Proc. Natl Acad. Sci. USA* **103**, 6581–6586. (doi:10.1073/pnas.0509716103)

Sears, K. E., Goswami, A., Flynn, J. J. & Niswander, L. A. 2007 The correlated evolution of *Runx2* tandem repeats, transcriptional activity and facial length in Carnivora. *Evol. Dev.* **9**, 555–565.

Shea, B. T. 1985 Bivariate and multivariate growth allometry: statistical and biological considerations. *J. Zool.* **206**, 367–390.

Smith, B. H. 1986 Dental development in *Australopithecus* and early *Homo*. *Nature* **323**, 327–330. (doi:10.1038/323327a0)

Smith, B. H. 2000 'Schultz's Rule' and the evolution of tooth emergence and replacement in primates and ungulates. In *Development, function, and evolution of teeth* (eds M. F. Teaford, M. M. Smith & M. W. J. Ferguson), pp. 212–227. Cambridge, UK: Cambridge University Press.

Smith, K. K. 2001 Heterochrony revisited: the evolution of developmental sequences. *Biol. J. Linn. Soc.* **73**, 169–186. (doi:10.1111/j.1095-8312.2001.tb01355.x)

Sondaar, P. Y. 1977 Insularity and its effect on mammal evolution. In *Major patterns in vertebrate evolution* (eds M. K. Hecht, P. C. Goody & B. M. Hecht), pp. 671–707. New York, NY: Plenum.

Stallibrass, S. 1982 The use of cement layers for absolute ageing of mammalian teeth: a selective review of the literature, with suggestions for further studies and alternative applications. In *Ageing and sexing animal bones from archeological sites* (eds B. Wilson, C. Grigson & S. Payne), pp. 109–126. BAR British Series 109.

Thewissen, J. G. M. & McLellan, W. A. 2009 *Maiacetus*: displaced fetus or last meal? *PLOS One* (Commentary 01 May 2009).

van Nievelt, A. F. H. & Smith, K. K. 2005 To replace or not to replace: the significance of reduced tooth replacement in marsupial and placental mammals. *Paleobiology* **31**, 324–346. (doi:10.1666/0094-8373(2005)031[0324:TRONTR]2.0.CO;2)

Vrba, E. S. 2004 Ecology, evolution, and development: perspectives from the fossil record. In *Environment, development, and evolution* (eds B. K. Hall, R. D. Pearson & G. B. Muller), pp. 85–105. Cambridge, MA: MIT Press.

Vrba, E. S. 2005 Mass turnover and heterochrony events in response to physical change. *Paleobiology* **31**, 157–174. (doi:10.1666/0094-8373(2005)031[0157:MTAHEI]2.0.CO;2)

Vucetich, M. G., Deschamps, C. M., Olivares, A. I. & Dozo, M. T. 2005 Capybaras, size, shape, and time. *Acta Palaeontol. Pol.* **50**, 259–272.

Wagner, G. P. 2007 The current state and the future of developmental evolution. In *From embryology to evo-devo. A history of developmental evolution* (eds M. D. Laubichler & J. Maienschein), pp. 525–546. Cambridge, MA: MIT Press.

Werdelin, L. 1987 Jaw geometry and molar morphology in marsupial carnivores: analysis of a constraint and its macroevolutionary consequences. *Paleobiology* **13**, 342–350.

Weston, E. M. 2003 Evolution of ontogeny in the hippopotamus skull: using allometry to dissect developmental change. *Biol. J. Linn. Soc.* **80**, 625–638. (doi:10.1111/j.1095-8312.2003.00263.x)

Weston, E. M. & Lister, A. M. 2009 Insular dwarfism in hippos and a model for brain size reduction in *Homo floresiensis*. *Nature* **459**, 86–88. (doi:10.1038/nature07922)

Wilson, L. A. B. & Sánchez-Villagra, M. R. 2009 Heterochrony and patterns of cranial suture closure in hystricognath rodents. *J. Anat.* **214**, 339–354. (doi:10.1111/j.1469-7580.2008.01031.x)

Wilson, L. A. B. & Sánchez-Villagra, M. R. 2010 Diversity trends and their ontogenetic basis: an exploration of allometric disparity in rodents. *Proc. R. Soc. B* **277**, 1227–1234. (doi:10.1098/rspb.2009.1958)